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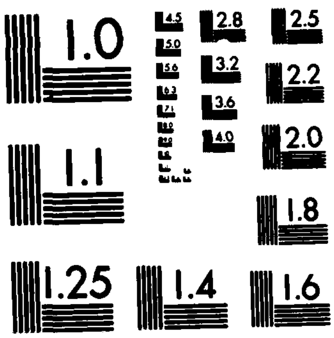

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EXCITATION OF T PHASES FROM SHALLOW AND INTERMEDIATE-DEPTH EARTHQUAKES IN THE SOUTHERN VANUATU (NEW HEBRIDES) ARC

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by

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In this paper, we present observations on the excitation of T phases from shallow and intermediate-depth earthquakes located along the southern Vanuatu (New Hebrides) island arc and recorded at short-period, vertical-component seismic stations on the Loyalty Islands of Lifou and Mare. Most of these earthquakes are part of the northeasterly dipping Benioff zone that defines the descending Australian plate in the upper 300 km of the mantle beneath the Vanuatu arc. The Loyalty Islands are uniquely situated on the oceanic Australian plate at distances of about 100 to 200 km in front of the southern Vanuatu trench axis. The main objectives of this study are: (1) to investigate in detail the nature and the pattern of the excitation of T phases from sources of considerably varying depths, and (2) to study the effects of submarine physiography on the observed pattern. This study was particularly desirable because of the relatively unique geometry of the sources and the recording stations and because the events used in this study are well-located using local land and ocean-bottom seismic networks (Coudert et al., 1981).

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The T phase is a high-frequency (about 2-100 Hz) compressional wave that propagates mainly in deep ocean low-velocity channels, like the SOFAR Channel (e.g., Ewing and Press, 1953; Shurbet, 1962). The waves travel in this oceanic wave-guide at the velocity of sound in water, about 1.5 km/sec. The depth to the axis of the low-velocity channel vaires between the different oceanic regions and also varies beteen summer and winter. For example, the depth to the axis is about 700 m near Hawaii and the minimum velocity is about 1.48 km/sec. The T phase is usually a train of waves that has a duration of about one minute or more. That the T phase propagates very efficiently for thousands of kilometers, even from relatively small explosive sources, is basically due to low attenuation and to the relatively low spatial spreading of sound energy as well as to the presence of the low-velocity SOFAR Channel that provides an idean wave guide for the sound energy. When the axis of the SOFAR channel is close to the surface of the water the increase of sound velocity with depth in the water provides the necessary wave guide for the efficient propagation of the T phase. Two mechanisms have been proposed for how the sound energy is introduced into the SOFAR Channel (e.g., Northrop, 1968). The first is the down-slope propagation mechanism, where P-type waves refracted into the water near the shelf are successively reflected down-slope until the rays become shallow enough to be confined to the water wave guide. The second mechanism is the surface scattering mechanism, where the refracted P-type waves are introduced into the water wave guide by scattering of energy along submarine physiographic features. For a given source area and a recording site the strength of T phases appear to correlate with the size of the sources (e.g., Johnson and Northrup, 1966). However, considerable variations are observed (e.g., Talandier and Okal, 1979; Adams, 1979). T phases are observed from shallow and deep events; the excitation of T phases from deep events

seems to occur near the trench axis (e.g., Shimamura and Asada, 1975). Considerable efforts were made to use the T phases to determine the hydroacoustic epicenters of the sources and to relate them to the seismic epicenters (e.g., Johnson et al., 1968; Northrop, 1968; Evernden, 1970).

The data used in this study are produced by two MEQ-800 smoked-paper seismographs located on the two Loyalty Islands of Lifou (LIF) and Mare (MAR). These two stations were part of a more extensive land and ocean bottom seismic network that operated along the southern part of the Vanuatu arc between August 7 and September 12, 1977. During this period 237 local earthquakes were recorded at LIF and MAR. Only 49 of these events were found to have produced T phases regardless of their depths, locations, and magnitudes. Not all the recorded events at LIF and MAR stations were located by the seismic network. In this study we have only studied in detail those events that are well-located by the temporary network (Coudert et al., 1981) and recorded by the Loyalty Islands' stations. Figure 1 shows some examples of the T phases recorded on the short-period, vertical component of the LIF station. The records are classified into six categories: (1) clear P,S, and T, (2) clear P,S, but weak T, (3) clear P,S, and no perceptible T, (4) clear P, weak and/or scattered S, and clear T, (5) clear P, weak and/or scattered S, but weak T, and finally (6) clear P, weak and/or scattered S, with no perceptible T. On all the records T phases are very emergent. This made our readings of the arrival times of T phases uncertain by several seconds. The seismic records revealed marked variations in the amplitudes of T phases relative to P and/or S waves (see Figure 2). Moreover, the duration of T phases, although difficult to determine exactly, showed no obvious correlation with the amplitudes of the T phases or the location or the depth of events.

Figure 3 shows the results of the excitation of T phases from shallow events (d $\leq$ 60 km). Earthquake epicenters were plotted with notations as to their location accuracy, and degree of presence or absence of T-phases. Large circles and squares indicate well-located events, whereas smaller circles and squares indicate the less well-located events. The record analyses reveal that when T-phases are observed, shallow sources tend to produce stronger T phases than deep sources. Shallow earthquakes whose hypocenters are not deeper than 60 km show a complete spectrum of possibilities for the excitation of T phases, where strong, weak, and no perceptible T phases are observed. In other words, different events from approximately the same source area show different possibilities of generating or not generating T phases. In addition, only 17 strong T phases from shallow earthquakes were noted, along with many weaker signals. On the other hand, intermediate-depth earthquakes show more consistent patterns by generating either weak or no perceptible T pahses (see Figure 4). The deepest earthquake that generated T phases in this investigation was about 280 km deep.

In this study we made an estimate of the positions of the conversion points from body waves to T phases between the hypocenters and the recording LIF station. We made this estimate for all events that are reasonably well-located and produced T phases that can be read on the LIF records. We assumed that the propagation paths of both the body waves and T phases are within the vertical plane between the events and the station. Tests were made to check whether slant-type propagation paths would result in a major change in the positions of the conversion points. The discrepancy was found to be negligible. Also we were unable to unambiguously determine whether P and/or S waves contributed mainly to the excitation of T phases. This is because of the realtively short travel path between the sources and the recording sta-

tions. Knowing the origin times of the events, the distance between the events and the LIF station, and the velocity of T phases, we determined the appropriate positions of the coversion points that best fit the observed travel time of T phases.

Plots of the T phase conversion points are shown in Figures 5 and 6 for shallow and intermediate-depth earthquakes, respectively. The striking feature of these plots is that most of the conversion points were found to be restricted to a zone bounded approximately by the 500-2000 fathom bathymetric contours. This suggests that the conversion was taking place at a certain zone, or "window", along the inner slope of the trench. The submarine physiography of this window appears to be favorable for the down-slope multiple reflections of the sound energy until the energy is introduced to the water wave guide as T phase energy, i.e., the down-slope propagation mechanism of Johnson et al. (1963). The location of this window also appears to be similar regardless of the depth of the hypocenters and the location of the epicenters. Figure 7 shows a cross section of the events used in this study as well as a detailed cross section of the submarine physiography. It is clear that shallow events that are located landward of the trench axis produce the strongest T phases. Apparently body waves produced by these events enter the T phase window along the inner trench slope at a more favorable angle for down-slope propagation, since several bottom reflections are required before SOFAR propagation is achieved. Figure 7 also shows that some of the shallow events and intermediate-depth events either produce weak T phases or that no T phases are observed from these events. The cause for this observation is not clear.

In summary this study provided a unique experiment to study the excitation of T phases from shallow and intermediate-depth events and observed at

stations located close and in front of the trench axis. We observed marked variations in the amplitudes of T phases relative to P and S waves. Only small fraction (about 20%) of the recorded local events produced T phases. Events that are very close to each other and are comparable in size sometimes produce T phases of different strengths and some of these events do not produce any perceptible T phases. In general, shallow events appear to systematically produce stronger T phases in comparison to intermediate-depth events. Of particular importance is that regardless of the depth of the hypocenters and the location of epicenters of those events that produce T phases we found that the positions of the conversion points from body waves to T phases are located in a zone bounded approximately by the 500-2000 fathoms submarine contours landward of the trench axis. This zone apparently provides an ideal T phase "window" for the down-slope multiple reflections before SOFAR propagation is achieved.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1: Examples of short-period, vertical-component seismograms showing P,S, and T phases recorded at the Loyalty Island of Lifou (LIF). The records are aligned along the P wave arrival times. The records are classified into six categories: (1) Clear P,S, and T (solid circles), (2) clear P,S, but weak T (half solid circles), (3) clear P,S, and no perceptible T (open circles), (4) clear P, weak and/or scattered S, and clear T (solid squares), (5) clear P, weak and/or scattered S, but weak T (half solid squares), (6) and finally, clear P, weak and/or scattered S, with no perceptible T (open squares).

Figure 2: A plot of T phase versus P wave amplitudes of shallow and intermediat-depth recorded at LIF station on the Loyalty Islands.

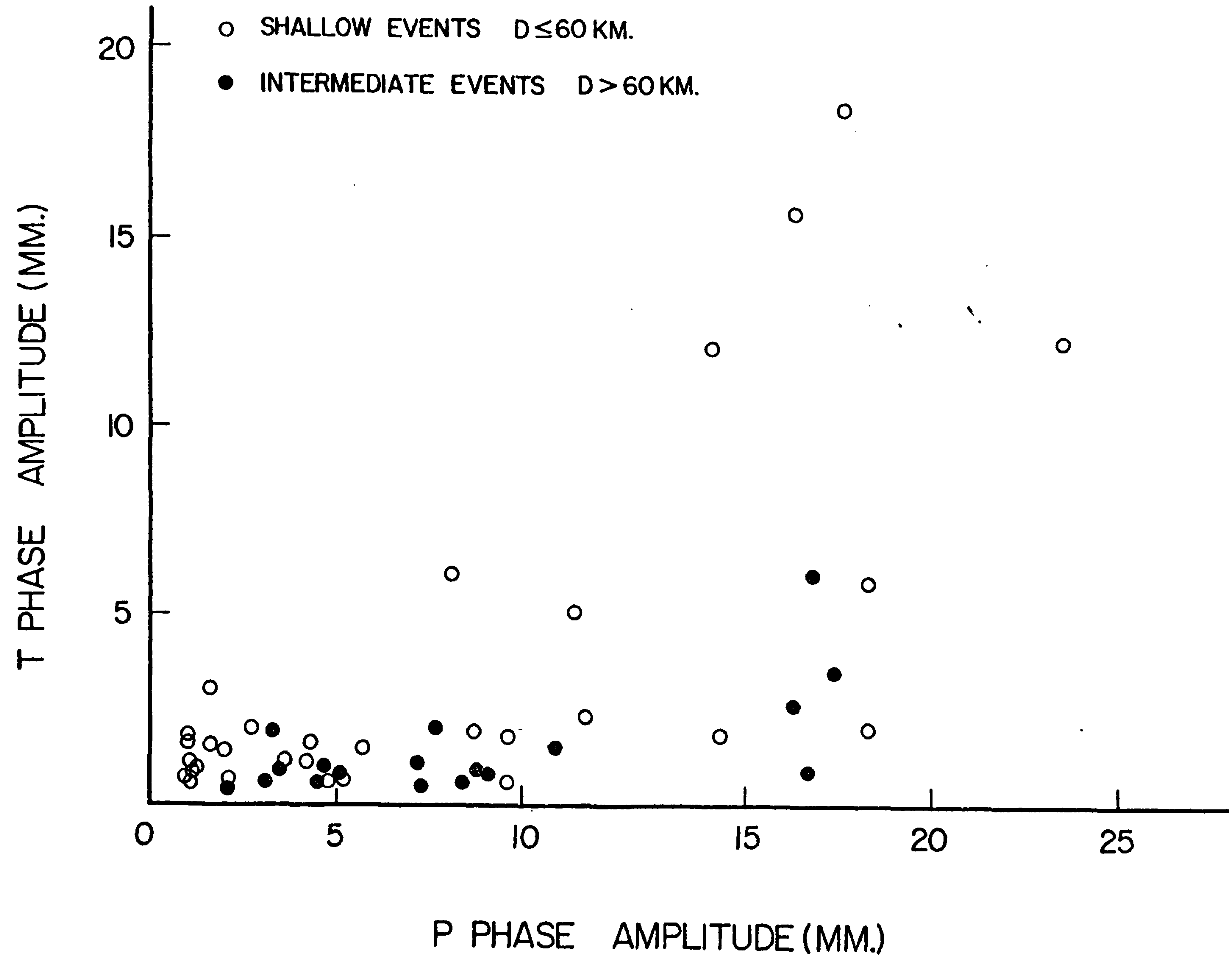
Figure 3: Map of the southern Vanuatu arc showing shallow events ($d \leq 60$ km) that are recorded at the Loyalty Islands' stations of Lifou (LIF) and Mare (MAR). The legend in the upper left hand corner explains the different categories of the excitation of T phases. These evnts are located by a temporary land and ocean bottom seismographs. The large symbols indicate well-located events. The submarine bathymetric contours are in fathoms. The location of cross section A of Figure 7 is also shown.

Figure 4: Map of the southern Vanuatu arc showing intermediate-depth events ($d > 60$ km) that are recorded at the Loyalty Islands' stations of Lifou (LIF) and Mare (MAR). Symbols are as in Figure 3.

Figure 5: Map of the southern Vanuatu arc showing the locations of T phase conversion points (solid crosses) from shallow events recorded at LIF station. Rest of symbols are as in Figure 3. Note that most of the conversion points are between about the 500-2000 fathom contours.

Figure 6: Map of the southern Vanuatu arc showing the locations of T phase conversion points (solid crosses) from intermediate-depth events recorded at LIF station. Rest of symbols are as in Figure 3.

Figure 7: Cross section perpendicular to the southern Vanuatu arc showing the hypocenters associated with the Vanuatu subduction zone and that are recorded at the Loyalty Islands' stations of LIF and MAR. The locations of the events are from Coudert et al. (1981). The arrows on top of the section indicate the projection of the positions of the local land and ocean bottom seismic stations used to locate the hypocenters. A detailed cross section of submarine topography along the trench of the seismicity cross-section is also shown. Rest of symbols are as in Figure 3. Note that events shallower than about 60 km produce all the well-recorded T phases. However, some shallow events and all of the intermediate-depth events either produce weak T phases or no perceptible T phases are excited by these events. Also note that the T phase "window", where most T phase conversion points are locat d, is situated above the shallow events that produce the stronger T phases.


SHALLOW EVENTS D ≤ 60 KM.
INTERMEDIATE EVENTS D > 60 KM.
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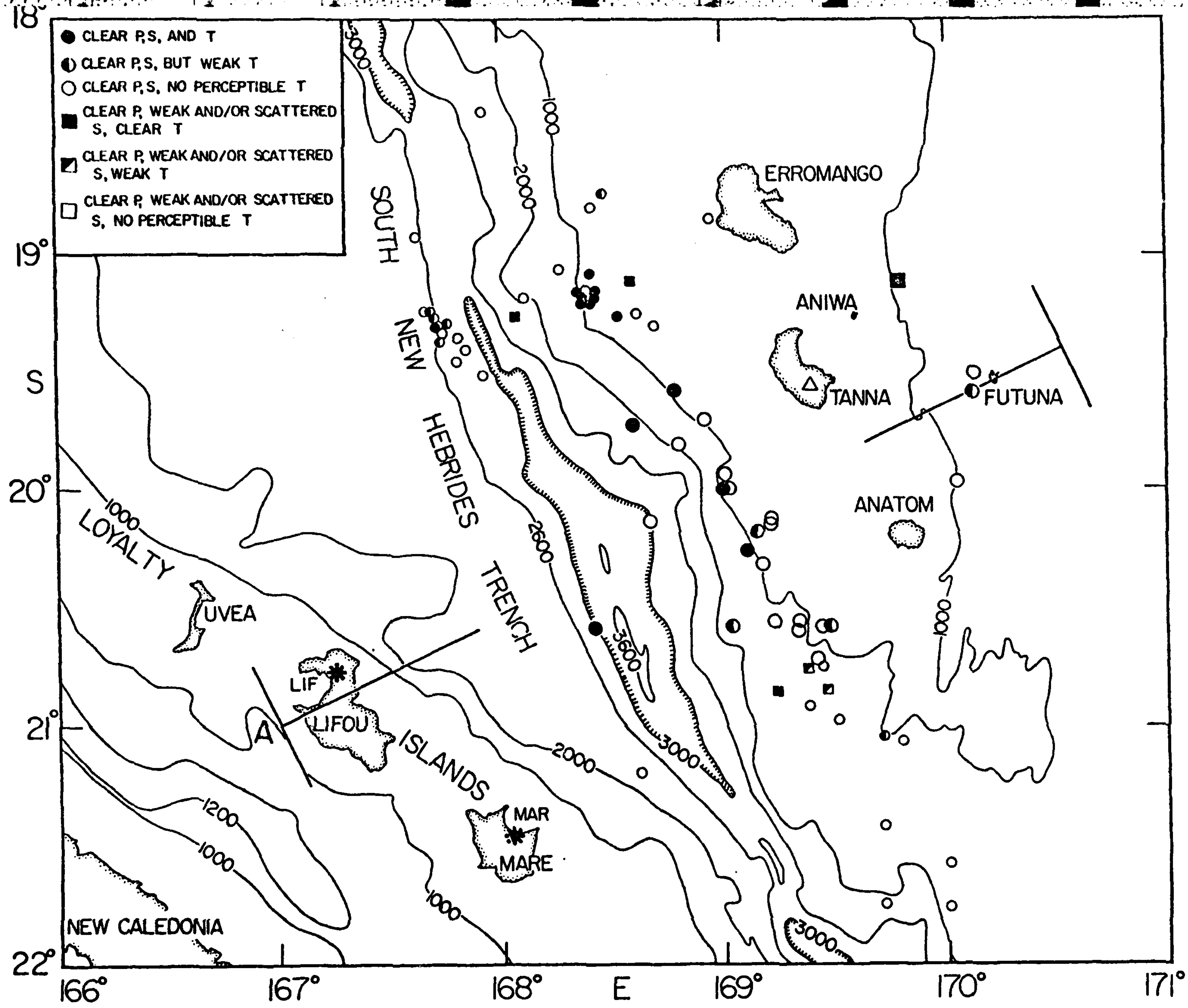
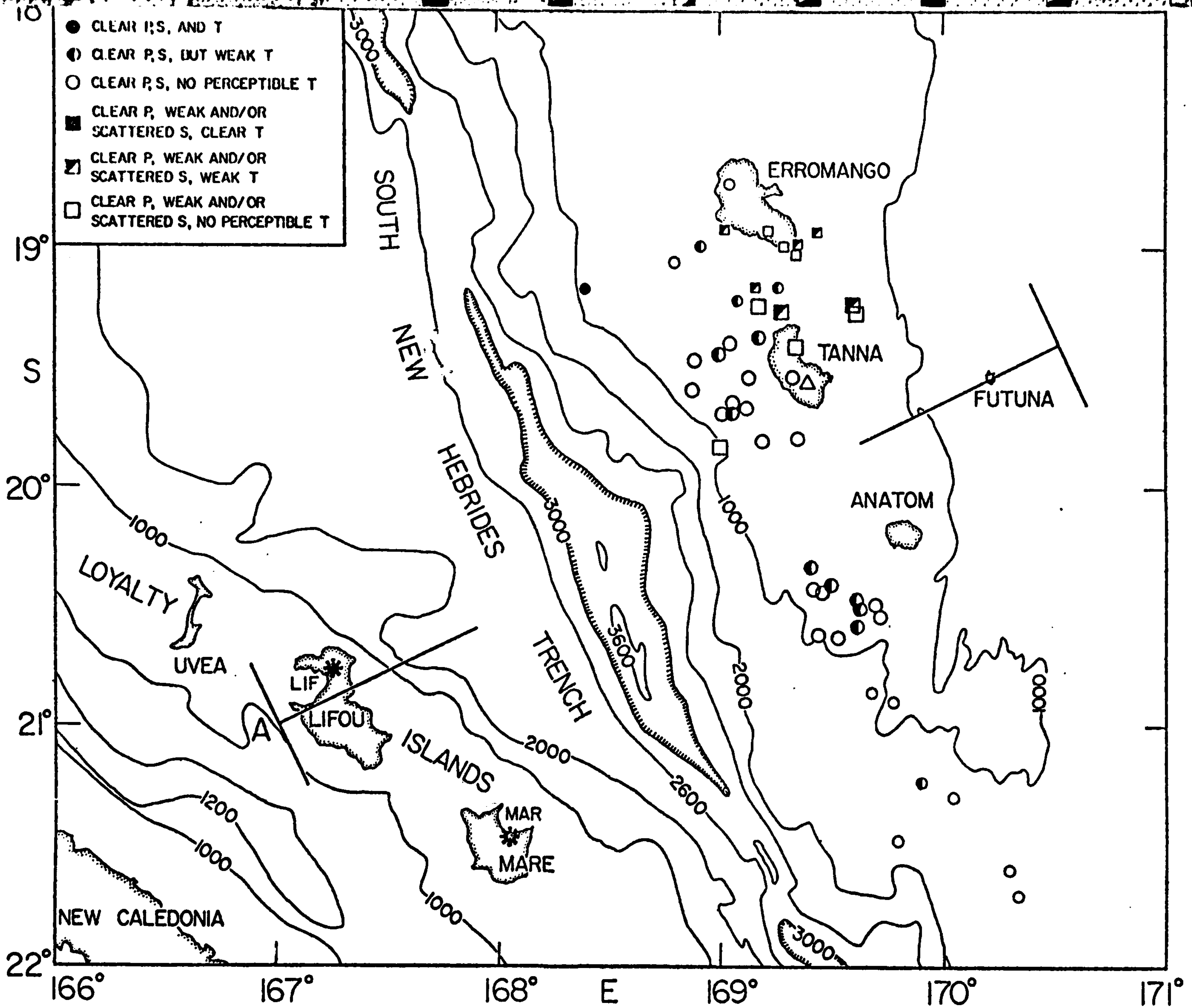
T PHASE AMPLITUDE (MM.)
P PHASE AMPLITUDE (MM.)

Fig. 2



DATA PRODUCED BY SHALLOW DEPTH EVENTS ($d \leq 60$ KM.)

Fig. 3



DATA PRODUCED BY INTERMEDIATE DEPTH EVENTS ($d \gtrsim 60$ KM)

Fig. 4

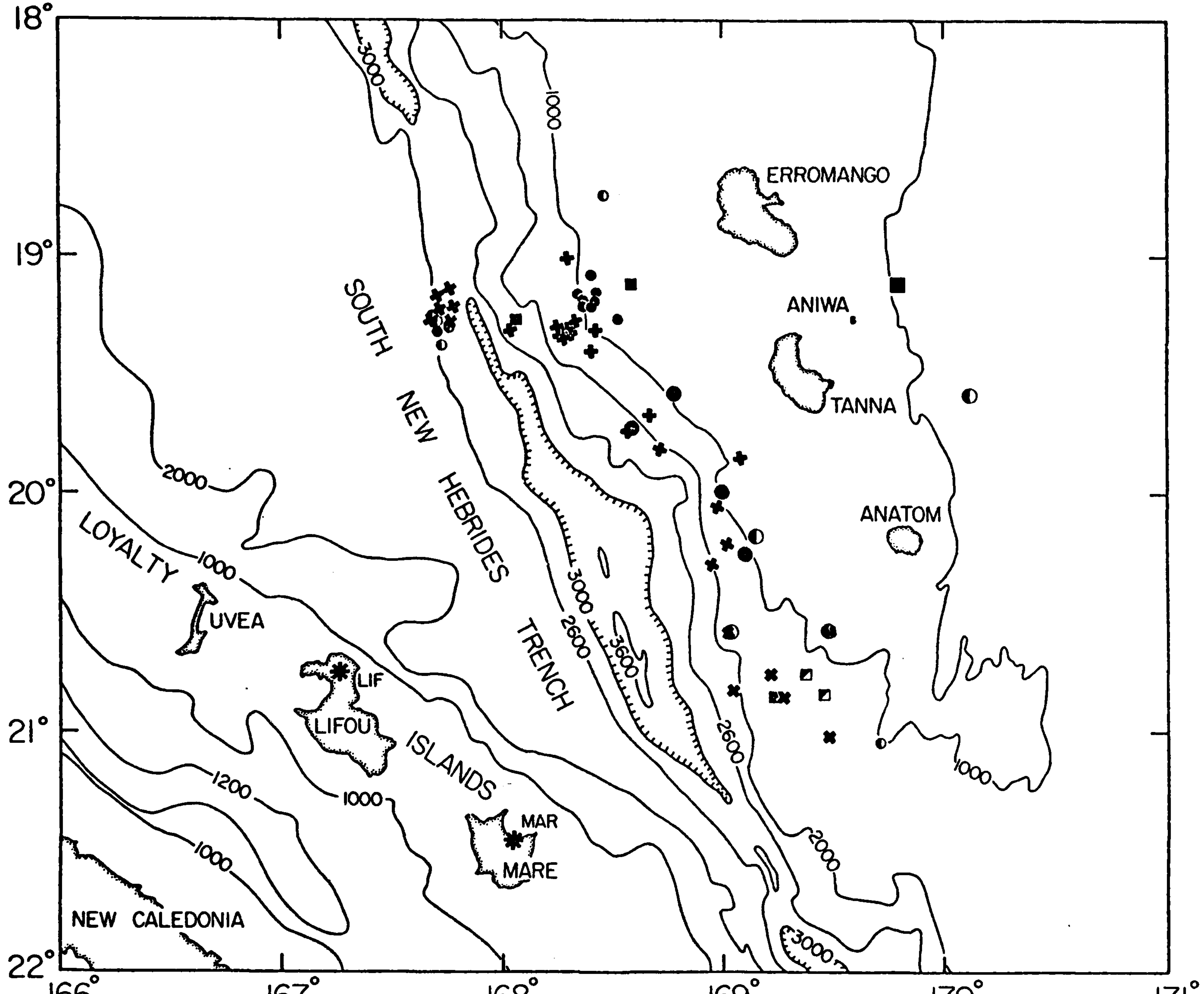

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Fig. 5

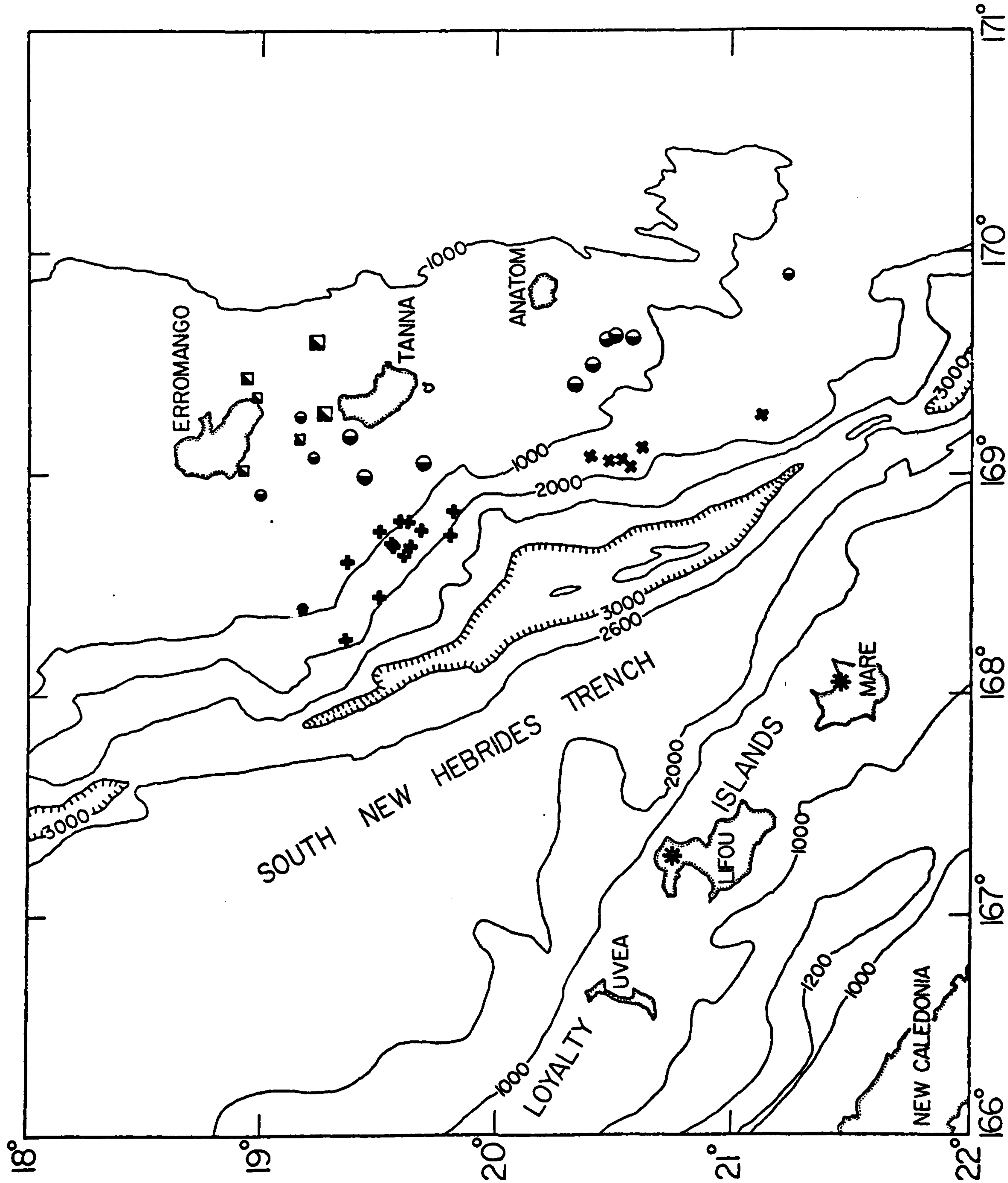

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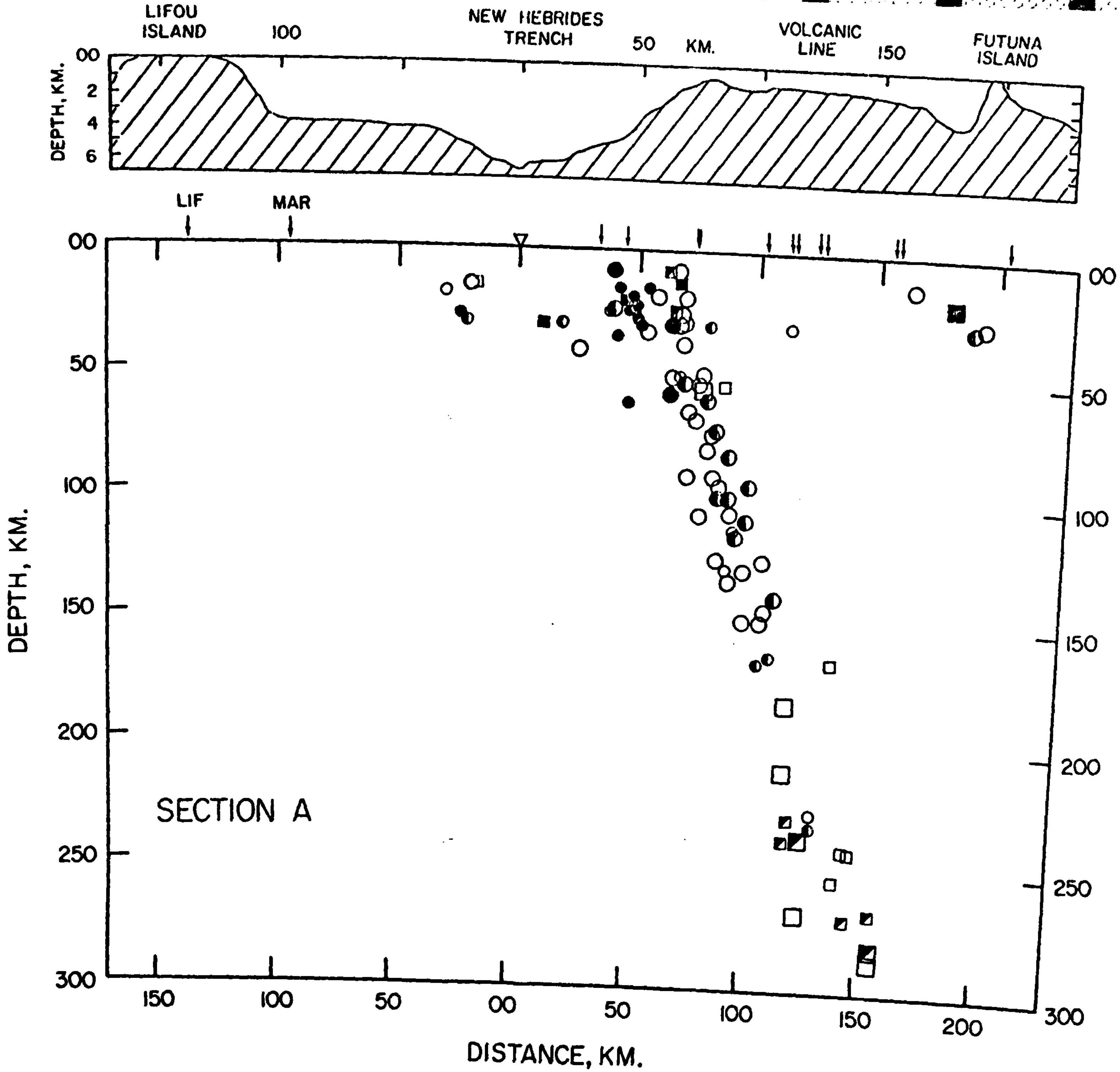
Fig.6



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SECTION A
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DISTANCE, KM.

Fig. 7